Dye penetrant crack detectability in external corners in presence of fillet radius

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ABSTRACT

NASA uses special dye penetrant nondestructive evaluation process to provide reliable detection of very small cracks. Typically the surface crack lengths sizes are 0.030” and 0.050” for special dye penetrant process. Qualification requires demonstration of crack detection on a set of cracks with average crack size smaller than or equal to the qualification crack size. The demonstration is called point estimate demonstration. A set of corner cracks can be used to determine reliably detectable corner crack using the point estimate demonstration method. However, dye penetrant demonstration on surface cracks can be used to assess reliably detectable corner crack sizes by using similarity in the penetrant process. The paper provides similarity analysis approach for determining the reliably detectable corner crack sizes for given a point estimate demonstrated surface crack size.

Keywords: dye penetrant, nondestructive evaluation, corner crack

1. INTRODUCTION

NASA uses special dye penetrant nondestructive evaluation (NDE) process to provide reliable detection of very small cracks. Here we consider an external corner only. Corner geometry is defined in the fracture mechanics analysis NASGRO® software as follows.

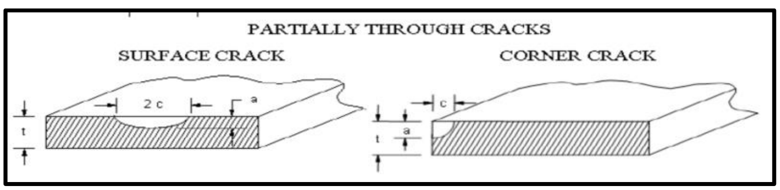

Fig. 1: Crack geometry for surface crack and corner crack in fracture mechanics

Without corner (or fillet) radius, i.e. $r = 0$, included angle θ between sides of the corner crack is 90°. The included angle increases as the fillet radius increases. At an angle of 180°, the geometry could not be called a corner. It is described as surface. Thus, as fillet radius increases, the corner crack geometry transitions to a surface crack. Included angle is determined by fitting a sector of a circle in the crack geometry. Center of radius of the sector is at center of surface length of the crack. Other two sector corners are located at ends of surface length of the crack. Included angle θ is angle of the sector. See Fig.2 below.

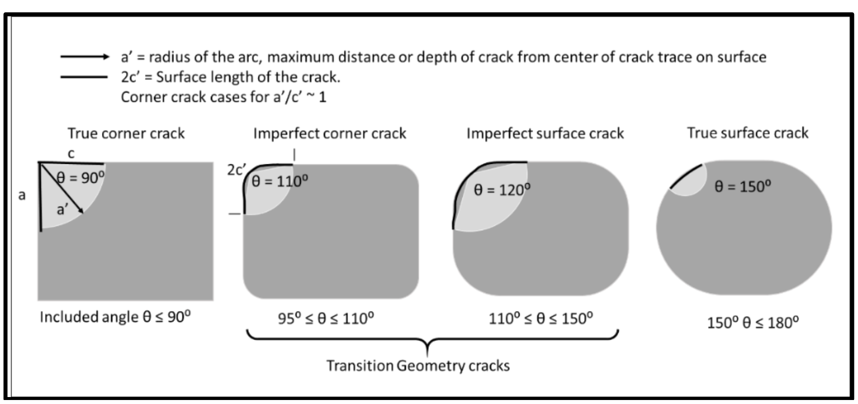

Fig. 2: Corner crack geometry with and without fillet radius and included angle θ

The corner crack geometry is further illustrated in Fig. 3. The sector is indicted by gray area in Fig. 3. We would refer to this geometry as “sector shaped crack”. For $\theta = 180°$, it is described as a half circle or thumb-nail crack.

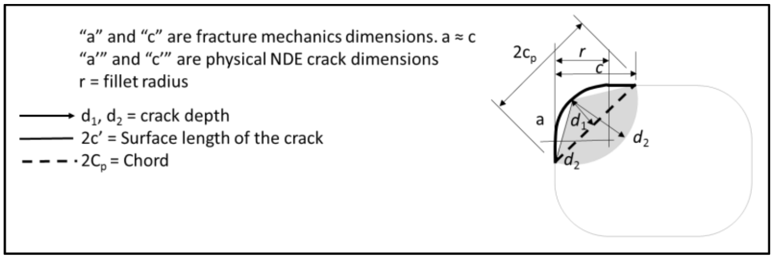

Fig. 3: Corner crack geometry and chord length

Here, demonstration is assumed to be performed on thumbnail 0.050” long x 0.025” deep (or 0.030” long x 0.015” deep) surface fatigue cracks in Titanium panels. Typically, a magnifier lens may be used to evaluate an indication after it is detected without using a magnifier lens. Fatigue cracks are assumed to be tight or the space between crack faces is very small; and the crack opening width is also very small i.e. < 0.0004”. The crack specimens are etched to a minimum 0.0004” depth. For demonstration of dye penetrant detection on cracks that are less than 0.050” in length, part configuration and material also shall be similar. Material finish of demonstration specimens shall be similar to the actual part surface finish. Fig. 4a shows a typical dye penetrant demonstration fatigue crack specimen. Fig. 3b shows a cylindrical configuration of crack specimens to simulate cylindrical liner inspection in the demonstration. Parker[1,2,3] provides data on dye penetrant fatigue crack detectability studies. These studies include variation in sensitivity level of dye penetrants, access configuration, corner crack sizes and crack depth.

Fig. 4: a) Demonstration fatigue crack specimen and b) demonstration configuration.

2. INSPECTION CASES AND SIMILARITY APPROACHES

2.1 Inspection Access Cases

Two inspection access cases need to be addressed.
Case 1: Both sides of corner are equally and adequately accessible for dye penetrant process.
Case 2: Only one side of corner is directly accessible for dye penetrant processing including evaluation such as surface outside a bolt hole. The other side of corner is called dye penetrant coverage “dead zone” region. Although, for higher values of fillet radius this region may be smaller than the region that is inspectable.

Corner crack size is determined based on similarity of corner crack to surface crack from point of view of dye penetrant inspection. Other than corner radius the surface finish is assumed to be comparable to that of the surface crack specimens. When we develop this approach for detection of corner crack and surface crack at corner, it shall have smooth change in crack size as the included angle changes from 0° to 180°. We assume that, for dye penetrant process, corner cracks behave as either corner cracks or surface cracks depending upon fillet radius. Fracture mechanics dimensions are defined for sharp corner, i.e. $r = 0$, cracks and are not defined for radiused corner cracks. Therefore, we need to define crack dimensions that are useful for both NDE and fracture mechanics. Assume $a = c$ and assume crack to be centered at center of the fillet curvature. Three similarity approaches are considered to determine the corner crack size based on demonstration of surface crack detection with crack length l_s.

2.2 Approach A. Surface Length Equivalency

Crack length is a primary resolution discriminator in penetrant indication compared to crack opening. Crack depth along with crack opening and length determine volume for dye penetrant that would be retained to form an indication. Since crack surface length provides footprint of the penetrant indication, it is more important than depth and crack opening. Longer and deeper cracks are also likely to be more open at the surface as crack is formed by propagation of the crack tip. Therefore, crack length has the highest influence on crack detectability.

Special dye penetrant (l_s = 0.030" to 0.050") crack is detected due to crack length primarily provided crack depth is ≥ 0.012". NASA JSC l_s = 0.030" set has mean crack length of 0.025" with mean depth of cracks 40% of the length or 0.010". Also, Parker[3] indicates that, for these special dye penetrant processes, a minimum crack depth of ~0.006" is needed for reliable crack detection.

Generally, many spurious indications are formed due to less than ideal penetrant process, surface scratches, and non-relevant discontinuities. These are shallow discontinuities or surface penetrant spot indications that can be discriminated by wiping the indication by an alcohol damped cotton swab. One can wipe the indication repeatedly to observe whether the indication reappears after swabbing. Shallow discontinuities or surface penetrant spot indications do not bleed penetrant upon wiping a couple of times. Deeper discontinuity indications would continue to bleed penetrant to surface and form indication even after half a dozen wipes. Therefore, deeper cracks can be detected reliably with low false call rate. If dye penetrant process is adjusted to detect shallow cracks, there is likely to be high false call rate due to surface scratches and roughness unless part surface finish is very high similar to mirror finish.

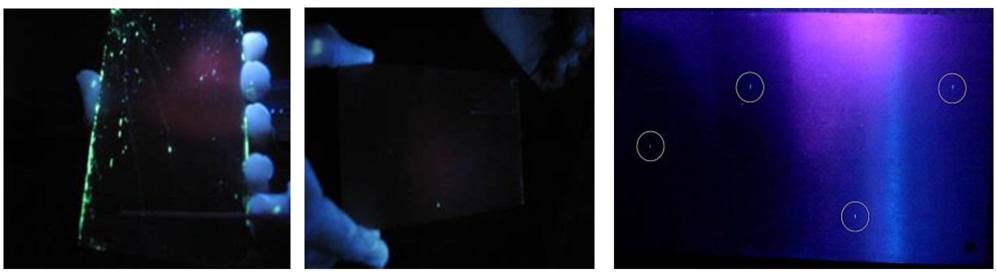

Fig. 5: a) dye penetrant indication with non-relevant indications and background, b) a dye penetrant indication without non-relevant indication and background, c) four faint dye penetrant indications without non-relevant indications and with low background florescence

Based on above rationale, a minimum depth of 0.012" is assumed for reliable crack detection for l_s = 0.030" or 0.050". Here, we assume that the surface crack length of a corner crack is greater than or equal to the demonstrated surface crack length l_s with depth greater than or equal to 0.012". This approach takes into account formation of penetrant indication but does not take into account the perceived length of the indication, which is discussed in Approach C.

2.3 Approach B. Crack Face Area Equivalency

Area equivalency is used in ultrasonic crack detection. Therefore, it is natural to think that it may be applicable to dye penetrant testing. Dye penetrant indication is formed due to retained volume of the penetrant which would be approximately proportional to the crack face area. Although, surface crack length and unsmeared or unclogged crack opening width are also important in crack detection. Dye penetrant developer can clog crack opening due to repeated use of crack panel provided cleaning of crack panel after each use is inadequate. Deeper cracks are also likely to be more open at the surface, as crack is formed by propagation of crack tip. The approach assumes that corner crack face area is same as that of the demonstrated surface crack face area. Obviously, one cannot choose much smaller crack length by increasing crack depth for area equivalency, as length $2c < l_s$ would result in a smaller indication which could be harder to detect. Therefore, we have to assume that crack length cannot be smaller than the demonstrated surface crack length l_s. Moreover, minimum depth shall also be 0.012". Since we must meet these two conditions, the equivalent area approach is considered to be constrained area equivalency approach. The approach would however give more conservative dimensions compared to Approach A as it also meets the requirements of approach A. Determining crack shape in the corner geometry is an issue. The crack geometry obtained from this approach shall have likelihood to form in the part under expected load spectrum. Therefore, we would limit the crack shape to a sector shaped crack. Currently, there is no known supporting evidence for area equivalency approach. Therefore, this approach is not as technically sound and seems to be more conservative.

2.4 Similarity Approach C: Projected Length Equivalency

Visual inspection would see only projected length of the indication at any viewing angle. This is also applicable to both cases. For Case 1, we use 45° as a typical angle of viewing corner providing balanced projection from both sides of the corner. Length of this projection is called chord length $2c_p$ here. See Fig. 3. 45° viewing angle gives the longest projection of the crack compared to 0 or 90 degree projections. Since we have assumed that both sides of crack are available for dye penetrant process including detecting indication, we select 45° as the viewing angle to have equal visibility of each side. In this approach we require that the chord length $2c_p$ is greater than or equal to the demonstrated surface crack length l_s. For other viewing angles, the inspection case is more like Case 2 where only one side is available for detecting crack. Approach C is more conservative than Approach A for small fillet radius. For large fillet radius the two approaches give about same surface crack lengths.

2.5 Mapping Fracture Mechanics Crack Size to NDE Crack Size

Fig. 3 provides definition of crack surface length ($2c'$), depth (d_1, d_2), chord length ($2c_p$), fillet radius (r), and top surface horizontal plane projected length (c). The horizontal plane projected length is provided to identify ends of the crack in relation to an imaginary corner point which corresponds to actual corner when fillet radius is zero.

If $r < c$, then folllowing equation maps the crack length $2c'$ along fillet radius.

$$2c' = 0.5\pi r + 2(c - r)\ . \tag{1}$$

d_1 and d_2 can be calculated as,

$$d_1 = 0.707c - 0.4142r, \text{ and} \tag{2}$$

$$d_2 = \sqrt{\frac{c^2}{2} + d_1^{\ 2}}\ . \tag{3}$$

Included angle can be calculated as,

$$\cos\left(\frac{\theta}{2}\right) = \frac{d_1}{d_2}. \tag{4}$$

Chord length is calculated by,

$$2c_p = 1.41c. \tag{5}$$

If $r \geq c$, then folllowing equation is used to map crack length along fillet radius

$$2c' \cong \theta r. \tag{6}$$

Crack face area can be approximately calculated by,

$$A \cong \frac{\theta {d_2}^2}{2}. \tag{7}$$

3. CACK SIZES FOR VARIOUS CASES AND APPROACHES

3.1 Case 1 Similarity Approaches

3.1.1 Case1, Approach A, Surface Length Equivalency

Primary assumption is that surface length of corner crack is greater than or equal to length of demonstrated surface crack l_s. Crack depth is greater than or equal to 0.012”. Calculations for l_s = 0.050” are shown below. Surface crack length $2c' \geq$ 0.050”.

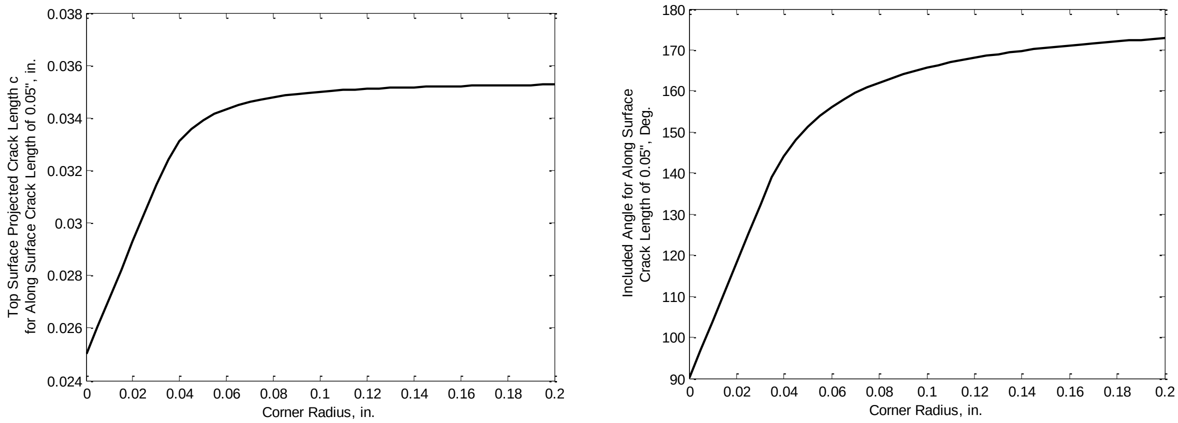

Fig. 6: a) Surface projected crack length and b) included angle as function of fillet radius for Case1, Approach A

3.1.2 Case 1 Approach B, Crack Face Area Equivalency

In this approach, corner crack face area is same as or larger than the demonstrated surface crack area. Minimum crack depth > 0.012”. Here, we use Case 1 Approach A as a condition in addition. Calculations for demonstartion of 0.050” surface crack length are shown below.

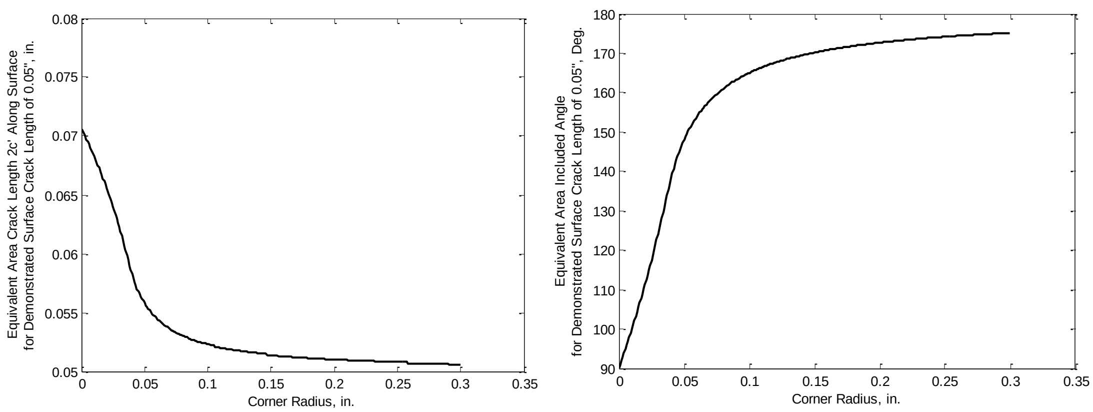

Fig. 7: a) Crack length along surface and b) included angle as function of fillet radius for Case 1, Approach B

3.1.3 Case 1 Approach C. Surface Length with Observable Chord Length Equivalency

This approach is based on 45° viewing angle projection for chord length. This is the length of indication used for crack detection. Crack depth is ≥ 0.012”. Surface length is ≤ $1.41l_s$. Calculations for demonstartion of l_s = 0.050” are shown below.

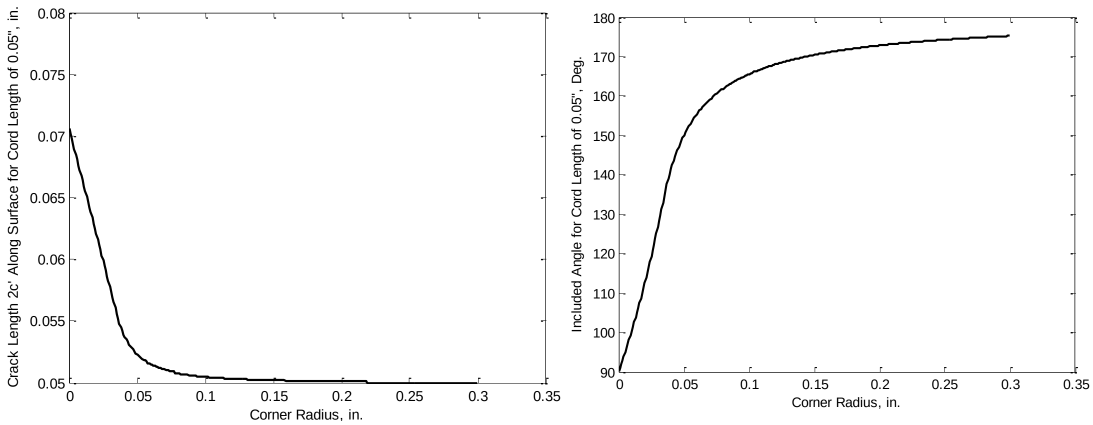

Fig. 8: a) Crack length along surface and b) included angle as function of fillet radius for Case1, Approach C

Table 1 provides selected values for Case 1. These values can be interpolated as needed for user applictaion.

Table 1: Case 1 Calculations

	Case Number, Approach, Demonstrated Surface Crack Size											
	1A, 0.030"	1A, 0.030"	1A, 0.050"	1A, 0.050"	1B, 0.030"	1B, 0.030"	1B, 0.050"	1B, 0.050"	1C, 0.030"	1C, 0.030"	1C, 0.050"	1C, 0.050"
r, in.	c, in.	θ, deg.	c, in.	θ, deg.	2c', in.	θ, deg.	2c', in.	θ, deg.	2c', in.	θ, deg.	2c', in.	θ, deg.
0.000	0.015	90	0.025	90	0.042	90	0.071	90	0.042	90	0.071	90
0.001	0.015	93	0.025	92	0.042	92	0.070	91	0.042	92	0.070	91
0.002	0.015	95	0.025	93	0.042	94	0.070	92	0.041	94	0.070	92
0.003	0.016	98	0.026	94	0.042	95	0.070	93	0.041	95	0.069	93
0.005	0.016	101	0.026	97	0.041	98	0.070	95	0.040	98	0.069	95
0.007	0.017	107	0.027	100	0.041	103	0.069	97	0.039	103	0.068	98
0.011	0.017	116	0.027	105	0.040	110	0.068	101	0.038	111	0.066	102
0.017	0.019	129	0.029	113	0.038	121	0.067	107	0.035	123	0.064	108
0.025	0.020	146	0.030	125	0.035	140	0.064	117	0.032	143	0.060	119
0.038	0.021	157	0.033	142	0.033	155	0.059	135	0.031	156	0.055	138
0.056	0.021	165	0.034	155	0.031	164	0.055	152	0.030	165	0.052	154
0.084	0.021	170	0.035	163	0.031	170	0.053	162	0.030	170	0.051	163
0.127	0.021	173	0.035	169	0.031	173	0.052	168	0.030	173	0.050	169
0.190	0.021	175	0.035	172	0.030	175	0.051	172	0.030	175	0.050	172
0.285	0.021	177	0.035	175	0.030	177	0.051	175	0.030	177	0.050	175

3.1.4 Comparison of Case 1 Approaches

Crack length along surface $2c'$ is 0.050" for Case 1 Approach 1. This is baseline level in Fig. 9a. Therefore, Fig. 9a shows crack length along surface for the three approaches. For approaches A and B, the crack length along surface is same for zero fillet radius and and for high values of fillet radius. At zero fillet radius, the crack length is $2c' = \sqrt{2}l_s$. The plot also shows that Approach B provides higher values of $2c'$ than Approach C. Approach C provides higher $2c'$ values than Approach A. Approach C seems to have better rationale of similarity than Approah B and therefore, would be preferred. Similarly, included angles are plotted to show that there is a smooth transition from 90° corner at zero fillet radius to 180° surface crack for high values of fillet radius. Larger crack sizes give smaller included angle for a given fillet radius.

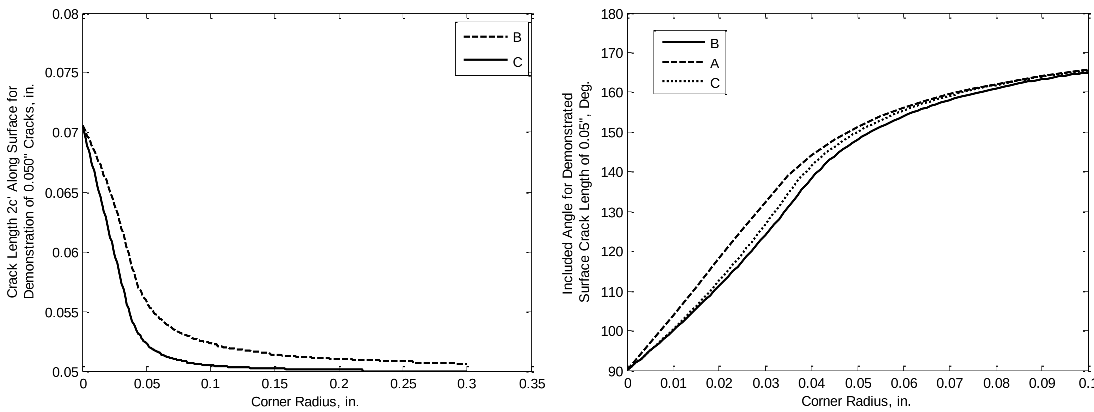

Fig. 9: a) Crack length along surface for Approach B and C and b) included angle as function of fillet radius for Case1 Approches A, B, C

3.2 Case 2 Approaches

Since one side of crack cannot be adequately detected, assume that accessible side is equivalent to the surface crack. We assume sector crack geometry.

3.2.1 Case 2, Approach A, Surface Length Equivalency

Here, only one side of the crack is inspectable. Using surface length equivalancy, length of inspectable side of corner crack equals length of equivalent surface crack. $l_s = c'$. Following two conditions apply. Crack depth is ≥ 0.012". Inspectable crack surface length, a or $c \geq l_s$. Plots shown below are sensible for small fillet radius and for assumption that one side of corner crack is not accesible for dye penetrant processing. This asumption does not work for larger fillet radius, e.g. greater than 0.06". In Fig. 10, the projected length c also includes part of length that is not inspectable.

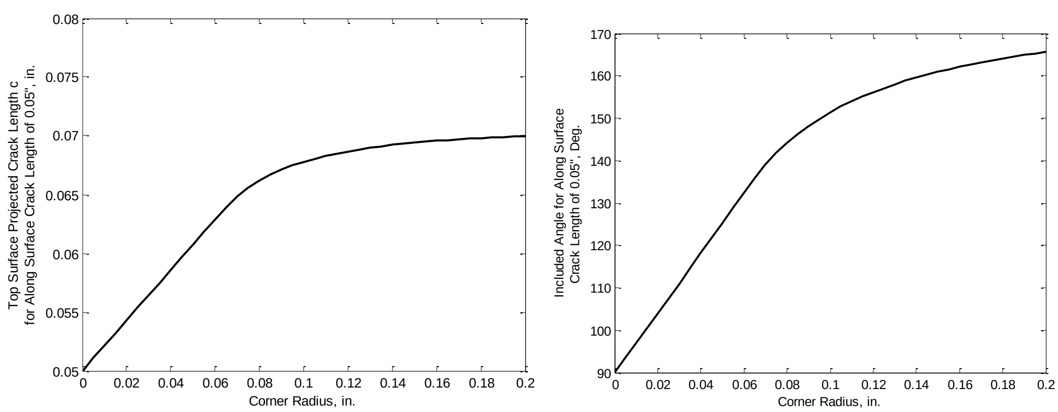

Fig. 10: a) Surface projected crack length and b) included angle as function of fillet radius for Case 2, Approach B

3.2.2 Case 2, Approach B, Crack Face Area Equivalency

The approach assumes that corner crack face area is same as or larger than that of the demonstrated surface crack face area. Here, we use Approach A for additional conditions. Therefore, for inspectable crack surface length, a or $c \geq l_s$.
Minimum crack depth is > 0.012". The plots shown below are sensible for small fillet radius and for assumption that one side of corner crack is not accesible for dye penetrant processing. This asumption does not work for larger fillet radius for example 0.06".
In Fig. 11, $2c'$ length along surface also includes part of the length that is not inspectable.

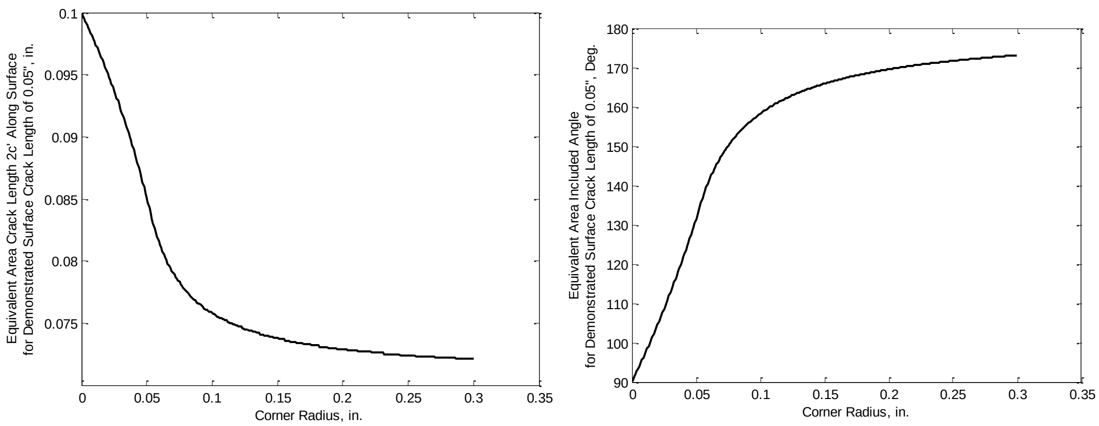

Fig. 11: a) Crack length along surface and b) included angle as function of fillet radius for Case 2, Approach B

3.2.3 Comparison of Case 2 Approaches

Both Case 2 approaches provide same size at zero fillet radius. As fillet radius increases, the crack size reduces from $2c'$ $= 2l_s$ to $2c' = \sqrt{2}l_s$ for Approach B. As fillet radius increases, the crack size remains constant i.e. $2c' = 2l_s$ for Approach A. Therefore, between two approaches of Case 2, Approach A is more conservative. Certain amount of judgement is needed on part of NDE engineer in assesing the dead zone region. Although, dye penetrant indication is also influenced by crack volume in uninspectable area, we do not take credit for it. Therefore, a less conservative Approach B seems to be a better choice. Table 2 provides selected values for Case 2.

Table 2: Case 2 Calculations

	Case Number, Approach, Demonstrated Surface Crack Size							
	2A, 0.030"	2A, 0.030"	2A, 0.050"	2A, 0.050"	2B, 0.030"	2B, 0.030"	2B, 0.050"	2B, 0.050"
r, in	c, in.	θ, deg.	c, in.	θ, deg.	2c', in.	θ, deg.	2c', in.	θ, deg.
0.000	0.030	90	0.050	90	0.060	90	0.100	90
0.001	0.030	92	0.050	91	0.060	92	0.100	91
0.002	0.030	92	0.050	91	0.059	93	0.099	91
0.003	0.031	94	0.051	92	0.059	94	0.099	92
0.005	0.031	96	0.051	93	0.059	96	0.099	93
0.007	0.032	98	0.052	95	0.058	99	0.098	95
0.011	0.032	103	0.052	98	0.057	103	0.097	98
0.017	0.034	109	0.054	101	0.056	111	0.096	102
0.025	0.035	119	0.055	107	0.053	123	0.094	109
0.038	0.038	134	0.058	116	0.048	143	0.090	119
0.056	0.040	149	0.062	130	0.046	157	0.083	138
0.084	0.042	160	0.067	146	0.044	165	0.077	154
0.127	0.042	166	0.069	157	0.044	170	0.075	163
0.190	0.042	171	0.070	165	0.043	173	0.073	169
0.285	0.042	174	0.070	170	0.043	176	0.072	173

4. CONCLUSIONS

The paper assumes that dye penetrant demonstration on surface cracks can be used to assess reliably detectable corner crack sizes by using similarity in the penetrant process. Given a demonstrated surface crack size, the paper provides

similarity analysis approaches for determining the reliably detectable corner crack sizes. Two inspection cases are considered.
Case 1: Both sides of corner are equally and adequately accessible for dye penetrant process.
Case 2: Only one side of corner is directly accessible for dye penetrant processing including evaluation.
Three approaches for Case 1, i.e. surface length equivalency, crack face area equivalency and surface length with observable chord length equivalency are provided. Two approaches for Case 2 i.e. surface length equivalency and crack face area equivalency are provided. Calculations were performed for demonstrated thumbnail crack length of 0.030” and 0.050”. For Case 1, Approach C is recommended and for Case 2, Approach B is recommended.

5. ACKNOWLEDGEMENT

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